INVESTIGATION OF PLASMA CONTACTORS FOR USE WITH ORBITING WIRES

Grant NAG9-126

Semiannual Report #2

For the period 1 July 1986 through 31 December 1986

Principal Investigator

Dr. Robert D. Estes

June 1987

Prepared for
National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
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1.0 INTRODUCTION

The SAO work carried out in the period covered by this report consisted of a continuation of our effort to determine the size and shape of the hollow cathode cloud emitted from an orbiting system. In addition we have applied results obtained for the ionospheric wave impedance of a tethered system to the experiments under consideration. We are still considering the recent plasma chamber experimental results reported by Urrutia and Stenzel [1986(a) and (b)]. These UCLA investigators have been calling into question the operating principles and feasibility of electrodynamic tethered satellite systems, based on their results, which show currents to be limited to values lower than those predicted by probe theory. While they do not specifically consider a system with hollow cathode devices, their rather sweeping claims of a fundamental flaw in the electrodynamic tethered satellite system concept could reasonably be extended to include such systems. Perhaps these results will be a stimulus to performing some carefully designed, high magnetic field experiments on hollow cathode devices in a plasma chamber. There is a plasma chamber at JSC/NASA of about the same size as the one used in the UCLA experiments and already equipped with coils capable of giving an axial magnetic field of 0.4-40 G [J. McCoy, private conversation 1986]. Our final report will discuss the UCLA results in the context of designing plasma chamber experiments.

One comment is worth making now. The supposed local circuit closure (across the magnetic field lines) observed in the UCLA experiments is a result that certainly cannot be extended to apply to the conditions of short tethers in space. The electrode separation in the UCLA plasma chamber was only 5 cm, or around 30 electron gyroradii. For TSS-1 type conditions with a 200 m tether, the

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separation would be — in terms of electron gyroradii — three orders of magnitude greater.

The experimental results referred to above are not the only challenge raised recently against the ability of an electrodynamic tethered satellite system to draw currents above a few milliamps from the ionosphere. Barnett and Olbert [1986] of MIT analyzed the radiation from an electrodynamic tethered satellite system operating in a constant current mode. They found that wave impedances were far greater than previously estimated, reaching as high as 10,000-100,000 ohms. This was due to a hitherto neglected band of frequencies lying between the lower hybrid and electron cyclotron frequencies, which the motion of the system would supposedly excite. SAO has examined this problem and determined that the large wave impedances obtained by Barnett and Olbert do not apply to a real electrodynamic tethered satellite system but are a result of their having considered the unrealistic case of an orbiting wire. We briefly summarize our results in this report, since they are relevant to the experiments being considered.

2.0 THE WAVE IMPEDANCE QUESTION

In addition to the problem of local charge exchange across the system/plasma boundaries considered independently of the "circuit closure" there is the problem of how the ionospheric plasma's global response to the moving disturbance represented by the electrodynamic tethered satellite system affects the system's ability to function as a power generator or thruster. In the models of hollow cathode devices developed so far, no attempt has been made to take into account the fact that an electrodynamic tethered satellite system, even when the current flowing through it is constant, causes a time-varying perturbation to the ionospheric plasma fields which generates electromagnetic plasma waves. A self-consistent theory that includes both the local plasma/system interactions and the large-scale perturbations caused by wave generation is a long way off, if not unattainable in practice. It is possible to estimate the effects of the plasma response on the functioning of the system, however, by calculating the wave impedance of the system under simplifying assumptions.

Barnett and Olbert [1986] considered the problem of wave generation by an electrodynamic tethered satellite system and found wave impedances in the range of 10kΩ, mainly due to radiation in a frequency band lying between the lower hybrid and electron cyclotron frequencies. These unexpectedly large wave impedances, if correct, would restrict tether currents to well below an ampere, even with very long tethers. This limitation would apply to the experiments we are presently considering.

SAO has been engaged in its own study of the tether wave generation problem, in mainly the context of deliberate, as opposed to incidental, generation of ULF/ELF waves. Our analysis can be found in detail in the final report for the NASA study NAG8-551. The SAO findings dispute the claim that an electrodynamic tethered satellite system would have a wave impedance of more than a few ohms. Since this issue is important for the short-tether experiments presently under consideration, we will summarize our results here.

The main point that comes out of our analysis is that modeling well the dimensions of the charge-exchange interfaces between the system and the ionospheric plasma is of fundamental importance for correctly obtaining the electromagnetic wave fields excited in the plasma. The electrodynamic tethered satellite system acts as a moving source (of opposite polarity at the two ends of the system) of external charge to the ionospheric plasma. It is the time-varying (because of the system's motion) fields generated by this charge at the tether ends that excites the waves generated by the system. The plasma responds to the perturbation with electromagnetic waves which carry the net charge density away from the system.

Thus wave generation is intimately connected with "circuit closure." The field-line currents are electromagnetic plasma wave packets with nonzero divergence of the electric field. The frequencies associated with the tethered system's perturbation of the ionosphere are determined by the time it takes for the charge-exchanging regions of the system to pass by the geomagnetic field lines. The larger the dimensions of these regions along the line-of-flight are, the lower is the maximum frequency associated with the disturbance. In practice these dimensions will be determined by the size of the terminating satellites or, more likely, by the size of the plasma contactor clouds.

This conclusion, which might be reached directly by physical reasoning, also emerges from the equations used in our analysis. It is also in the equations of Barnett and Olbert, but they evidently didn't draw the physical conclusion from it, since they modeled the tethered satellite system in an unrealistic way. They considered it to be a long, narrow cylinder, i.e., an orbiting wire. In effect they reduced the charge-exchange surface of the system to the cross-section of the wire at its two ends. It is the small dimensions of the charge-exchange region in their model that makes the higher frequency band so important in their analysis and causes them to obtain the very high wave impedances. For a system with charge-exchange region dimensions of a few meters, radiation in the band that is so important in the analysis of Barnett and Olbert becomes negligible.

This is not to deny that the Barnett and Olbert analysis is an important contribution. The exclusion of radiation (generated by a constant tether current) in the frequency band between the ion cyclotron and the lower hybrid frequencies is a significant conclusion (within the framework of cold plasma theory) that does not depend on the system dimensions used in the model.

Wave impedances for a realistic model of the tethered system are around 0.4Ω for a tether 10 km long in the daytime central F-region. The dependence on tether length and terminating dimensions is weak. The wave impedance is linear in the Alfvén speed, so increases by a factor of ten above the value quoted above might occur within a single orbit, based on the studies of electron density variation. However, the model is highly idealized. At this point its best use, perhaps, is to show that the Barnett and Olbert results, which were obtained with the same assumptions, are not applicable to a real tethered satellite system, and thus cannot be taken as proof that an electrodynamic tethered satellite system won't work.

3.0 SIMPLE PLASMA KINETIC MODEL FOR PLASMA CONTACTOR CLOUD*

In our previous report for this investigation (Section 3.4) we considered the emission of the hollow cathode gas into the streaming ionospheric gas within the framework of a fluid model. This gave us a lower limit on the "standoff distance" to which the hollow cathode expands against the atmospheric stream. For the parameters considered in the earlier report this was only 20 cm. We note that this quantity varies inversely with the square root of the atmospheric mass

*Contributed by Prof. Robert Hohlfeld

density. Increasing the altitude from the 220 km considered in the previous study up to 300 km (TSS-1 height) results in a ten-fold increase in the fluid model standoff distance to 2 meters.

In the present analysis we estimate an upper limit to the standoff distance based on the opposite extreme of "weakly interacting" gas particles in the kinetic theory approach sketched below.

Let the plasma contactor rest at the center of the coordinate system. We will work in a reference frame moving with the plasma contactor.

Take the Shuttle flying in the $+\hat{e}_x$ direction, and so the flow of ionospheric material past the plasma contactor cloud has velocity $-V_{orb}\,\hat{e}_x$, where V_{orb} is the orbital velocity of the Shuttle.

Begin by writing down the ionospheric distribution function (in the absence of a plasma contactor cloud and the contactor cloud distribution function in the absence of interaction with the ionosphere). Thermal velocity spreads can be neglected for both distribution functions, at least for the initial treatment.

The thermal spread of the ionospheric distribution function may be neglected because the Shuttle motion with respect to ionospheric material is highly supersonic. Consider a typical ionospheric species as represented by oxygen atoms at a temperature of 10^3 °K.

$$m \simeq 16\ m_p \doteq 2.67 \times 10^{-23}\ gm$$

$$V_{th} \simeq \sqrt{3\ kT/m} = \left(\frac{3(1.38\times10^{-16}\ erg/^{o}K)(10^{3}\ ^{o}K)}{2.67\times10_{o}{}^{-23}\ gm}\right)^{1/2}$$

$$= 1.24 \times 10^5 \ cm/\sec = 1.24 \ km/\sec$$

$$\frac{V_{orb}}{V_{th}} \simeq \frac{8 \ km/\sec}{1.24 \ km/\sec} = 6.43$$

Although this is not an enormously large number, it is still probably possible to neglect ionospheric thermal velocities.

The calculations on the adiabatic expansion of the plasma contactor cloud show the contactor cloud to be very cold, furthermore, its expansion velocity

$$v_{exp} \approx 2.5 \times 10^4 \ cm/\sec \ (\textit{see calculation in previous report})$$

satisfies

$$\frac{V_{orb}}{v_{ex}} \approx \frac{8 \times 10^5 \ cm/\sec}{2.5 \times 10^4 \ cm/\sec} = 32$$

Therefore, we may to an excellent approximation, neglect the thermal velocities of the plasma contactor cloud and also neglect any velocity dependence of collision cross-sections in treating particles traveling in the $\pm \ \hat{e}_x$ directions.

Begin by adopting a model in which the interaction between the plasma contactor and the ionospheric flow is "weak." In this model calculation wherever a scattering occurs between a contactor cloud particle and an ionospheric particle, the recoil velocities are large compared to any other velocities in the problem except the orbital velocity. The scattered particles are assumed to leave the system "instantaneously" without further scattering. This sort of "weak interaction single-scattering" limit is clearly not realistic throughout the volume of the plasma contactor cloud and will yield an overestimate of the plasma contactor cloud size. This may be useful, however, as the fluid-dynamic calculation of the previous report bounds the size of the plasma cloud from below. It may be possible to obtain a reasonable estimate of the plasma contactor cloud bounded by these two limits.

The distribution function of the ionospheric background, in the absence of interaction with the plasma contactor cloud may be written:

$$F_b\left(\vec{x},\vec{v}\right) = N_o\,(\vec{x})\ \delta\left(v_x - v_{orb}\right)\ \delta\left(v_y\right)\ \delta\left(v_z\right) \tag{1}$$

It will be assumed that a steady state solution ($\partial/\partial t = 0$) can be found for the density distribution. Here $N_o(\vec{x})$ = background number density of particles (particles/cm^3), the spatial dependence of $N_o(\vec{x})$ (derivation from $N_o(\vec{x})$ = constant) is determined by scattering with the plasma contactor cloud. For purposes of this calculation it can be assumed that the background is composed of a single neutral atomic species, e.g. atomic oxygen.

Define distribution functions for electrons, ions, and neutral atoms in the plasma contactor cloud as $f_e(\vec{x},\vec{v})$, $f_i(\vec{x},\vec{v})$, and $f_n(\vec{x},\vec{v})$ respectively. However, as ionization and recombination processes may be expected to be negligible outside the plasma contactor itself, we can refer to these generically as $f(\vec{x},\vec{v})$. Again we are initially concerned only with stationary solutions. The (unperturbed) number density of the plasma contactor cloud particles is proportional to r^{-2}, owing to conservation of particle fluxes, i.e.

$$n(r) = n_o(r_o) \ (r_o^2/r)^2 \tag{2}$$

where n_o and r_o are reference values of number density and radius chosen to avoid the unphysical singularity at $r = 0$. The values of n_o and r_2 are chosen on the basis of the mass flow rate and other properties of the plasma contactor, as outlined in the calculation of 10 October 1986. Then the plasma contactor cloud distribution function may be expressed in spherical coordinates as

$$f(\vec{x}, \vec{v}) = n(r) \ \delta(v_r - v_{\text{exp}}) \ v_{\text{exp}}{}^{-2} \tag{3}$$

where v_r is the radial velocity and v_{exp} the velocity of expansion of the plasma contactor cloud particles. Expressing the distribution function in rectangular coordinates

$$\begin{aligned} f(\vec{x}, \vec{v}) &= n(r) \ \delta\left(v_x^2 + v_y^2 + v_z^2 - v_{\text{exp}}{}^2\right)/v_{\text{exp}} \\ &= n(r) \ \delta\left(\sqrt{v_x^2 + v_y^2 + v_z^2 - v_{\text{exp}}}\right)/v_{\text{exp}}{}^2 \end{aligned} \tag{3$'$}$$

The evolution of the distribution functions $f(\vec{x}, \vec{v})$ and $F_b(\vec{x}, \vec{v})$ are then described by the Boltzmann equations for each distribution function.

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla} f + \vec{a} \cdot \frac{\partial}{\partial \vec{v}} f = \frac{\delta f}{\delta t}\Big|_{coll} \tag{4a}$$

$$\frac{\partial F_b}{\partial t} + \vec{v} \cdot \vec{\nabla} F_b + \vec{a} \cdot \frac{\partial}{\partial \vec{v}} F_b = \frac{\delta F_b}{\delta t}\Big|_{coll} \tag{4b}$$

In this simple model it is assumed that there are not forces acting on particles except during collisions (i.e. no plasma waves or plasma turbulence) $\rightarrow$ $a = 0$, and we seek a stationary solution $\rightarrow$ $\partial/\partial t = 0$

$$\vec{v} \cdot \vec{\nabla} f = \frac{\delta f}{\delta t}\Big|_{coll} \tag{5a}$$

$$\vec{v} \cdot \vec{\nabla} F_b = \frac{\delta F_b}{\delta t}\Big|_{coll} \tag{5b}$$

Physical interpretation:

Particles travel along linear phase space trajectories except when removed from their respective distributions by a collision. Each collision removes a particle from the plasma contactor distribution and a particle from the ionospheric distribution

$$\frac{\delta f}{\delta t}\Big|_{coll} = \frac{\delta F_b}{\delta t}\Big|_{coll} \tag{6}$$

(Only binary collisions are considered, and since the species chosen to represent the background distribution is a neutral atom, long-range interactions between particles are ignored.) Both $\frac{\delta f}{\delta t}\Big|_{coll}$ and $\frac{\delta F_b}{\delta t}\Big|_{coll}$ will in general depend on $\vec{x}$ directly and indirectly through the value of the other distribution function. However, the sense in which we should consider the interaction of the distributions is weak is that we shall neglect variations in F_b in calculating $\frac{\partial f}{\partial t}\Big|_{coll}$. We can then use the value of f to calculate a solution for F_b and thus proceed iteratively until we achieve some solution for f and F_b. This iterative process may converge if the interaction of the two populations is sufficiently weak. The full iterative process will doubtless have to be carried out on a computer, but useful analytic results should be obtained by considering the first few iterations. The collisions of interest for this system are:

1) atom-atom collisions
2) atom-election collisions
3) atom-ion collisions

Since at least one of the particles is neutral in each of these three possibilities and the range of velocities is not very great, we will treat a collision (of whatever type) as being characterized by a collision cross section σ, independent of velocity (approximately) and different for each type of collisions. For the 1st iteration consider the density distribution in the plasma contactor cloud arising from F_k = const. The near free path of the plasma contactor cloud particles is

$$\lambda = 1/N\sigma \tag{7}$$

where N is the number density of ionospheric particles.

Estimate λ numerically. For standard Shuttle conditions at an altitude of 220 km ($N = 4\times10^{10}$ cm^{-3}) these cross sections should be approximated by a typical gas kinetic cross section: $\sigma \approx 3\times10^{-14}$ cm^2, which gives

$$\lambda = (4\times10^{10}\times3\times10^{-14})^{-1}\ cm = 833\ cm = 8.33\ m$$

which implies that we're going to get a reasonable scale length for the cloud. For the conditions for TSS-1, the height is 300 km $\rightarrow N = 5\times10^{8}$ cm^{-3} $\rightarrow$

$$\lambda = 667 \;\; m = 0.667 \;\; km$$

the plasma contactor density in this limit may be written down by inspection:

$$n(r) = n_o \; (r_o/r)^2 \; e^{-r/\lambda} \tag{8}$$

We can calculate a characteristic scale size for the cloud from (8)

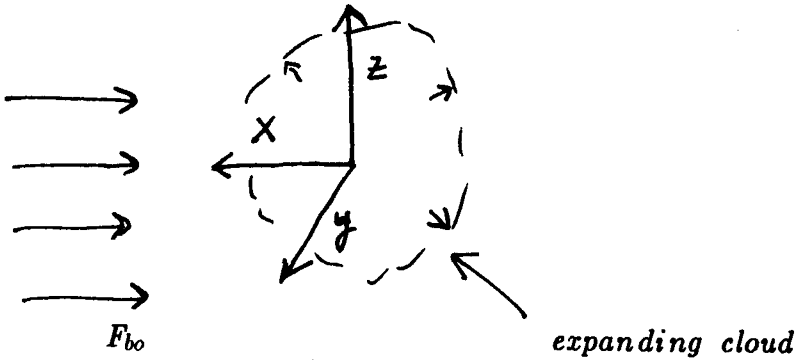
$$\left|\frac{1}{n}\frac{dn}{dr}\right|^{-1} = \left|\left\{\left[n_o^{-1}\left(\frac{r}{r_o}\right)^2 e^{r/\lambda}\right]\left[n_o\left(-2(r_o/r)^2 e^{-r/\lambda}\right) + (r_o/r)^2 \; (-1/\lambda)e^{-r/\lambda}\right]\right\}^{-1}\right|$$

$$= \left|\left(-\frac{2}{r} - \frac{1}{\lambda}\right)^{-1}\right| = \left|\frac{-1}{2/r + 1/\lambda}\right| = \left|\frac{-r\;\lambda}{2\lambda + r}\right| = \frac{r\lambda}{2\lambda + r} \tag{9}$$

note that as $r\rightarrow\infty$, scale size$\rightarrow\lambda$; as $r\rightarrow 0$, scale size$\rightarrow r/2$

However, it is not surprising that the scale size is a function or r.

We must now take this calculation to one higher iteration (at least) to get useful information about deviations from spherical symmetry



Initially consider that any scattering which occurs between plasma contactor cloud particles and ionospheric particles has the effect of subtracting a particle from the ionospheric beam. Let

F_{bo} $\equiv$ *unperturbed ionospheric background distribution function*

$$F_b\left(x,y,z\right) = F_{bo}\ \exp\left[-\left(\int_{\infty}^{z}\frac{d_z\prime}{\lambda(x\prime,y,z)}\right)\right] \tag{10}$$

$\lambda(r)=\dfrac{1}{n(r)\sigma}$ *with* $n(r)=$ *initial iteration of contactor cloud distribution*

$$n(r) = n_o\left(r_o/r\right)^2\ e^{-r/\Lambda},\ \textit{where}\ \Lambda=1/N\sigma$$

is the initial mean free path estimated above.

$$r = \sqrt{x^2+y^2+z^2}\ ,\ r\prime = \sqrt{x\prime^2+y^2+z^2}$$

Note that y,z = constant along an integration path. Let $b = \sqrt{y^2 + z^2}$, which has the role of an "impact parameter"

$$F_b\left(x, y, z\right) = F_{bo} \exp\left(-\int_\infty^x dx' \; n(r')\sigma\right)$$

$$= F_{bo} \exp\left[-n_o r_o^2 \sigma \int_\infty^x dx' \; \frac{\exp(-1/\Lambda \sqrt{x'^2 + b^2}\,)}{x'^2 + b^2}\right] \tag{11}$$

Begin by considering $b = 0$, i.e. the density distribution along the x axis.

$$F_b(x) = F_{bo} \exp\left[-n_o r_o^2 \sigma \int_\infty^x dx' \; \frac{\exp(-x'/\Lambda)}{x'^2}\right] \tag{12}$$

From standard integral tables,

$$\int \frac{e^{ax}}{x^m}\, dx = \frac{-1}{m-1}\, \frac{e^{ax}}{x^{m-1}} + \frac{a}{m-1} \int \frac{e^{ax}}{x^{m-1}}\, dx$$

In this simple-minded model the density of the chemical release cloud is infinite at the origin, and so $F_b(\lambda)$ must go to zero at positive x. Will assume in what follows that when $b = 0$, $x > 0$.

$$\int_\infty^x dx' \; \frac{\exp(-x'/\Lambda)}{x'^2} = (-1)\, \frac{e^{-x'/\Lambda}}{x'} \Bigg|_\infty^x - \frac{1}{\Lambda} \int_\infty^x \frac{e^{-x'/\Lambda}}{x'}\, dx$$

$$= -\frac{1}{x}\, e^{-x/\Lambda} + \left(\frac{1}{\Lambda}\right) \int_{x/\Lambda}^\infty \frac{1}{t}\, e^{-t}\, dt$$

$$= -\frac{1}{x}e^{-x/\Lambda} + \frac{1}{\Lambda}E_1(x/\Lambda)$$

(See Abramowitz and Stegun, Chapter 5, pp. 227ff.)

$E_1(x)$ has a series expansion:

$$E_1(x) = -\gamma - \ln x - \sum_{n=1}^{\infty} \frac{(-)^n x^n}{n\ n!}$$

as

$$x \to 0 \qquad E_1(x) \to \infty$$

as

$$x \to \infty \qquad E_1(x) \to 0$$

Which guarantees proper limiting behavior for $F_b(x)$

$$F_b(x) = F_{bo}\ \exp\left\{n_o^2 r_o^2 \sigma\left[\frac{1}{\Lambda}E_1(x/\Lambda) - \frac{1}{x}e^{-x/\Lambda}\right]\right\} \tag{13}$$

Note that (13) gives us $F_b(x) < F_{bo}$ for all $x < \infty$, ($x > 0$) as we would expect on physical grounds.

Figure 1 displays the results of some calculations using the expressions derived above. The ionospheric particle density along the line of flight ahead of the plasma contactor (x measured in units of Λ) is shown for five different values of $a = n_o^2 r_o^2 \sigma/\Lambda$: a=10, 3, 1, 1/3, and 1/10. The curves for large a values lie below the curves for small s values as would be expected, since large a values correspond to larger values of the mass flux from the plasma contactor.

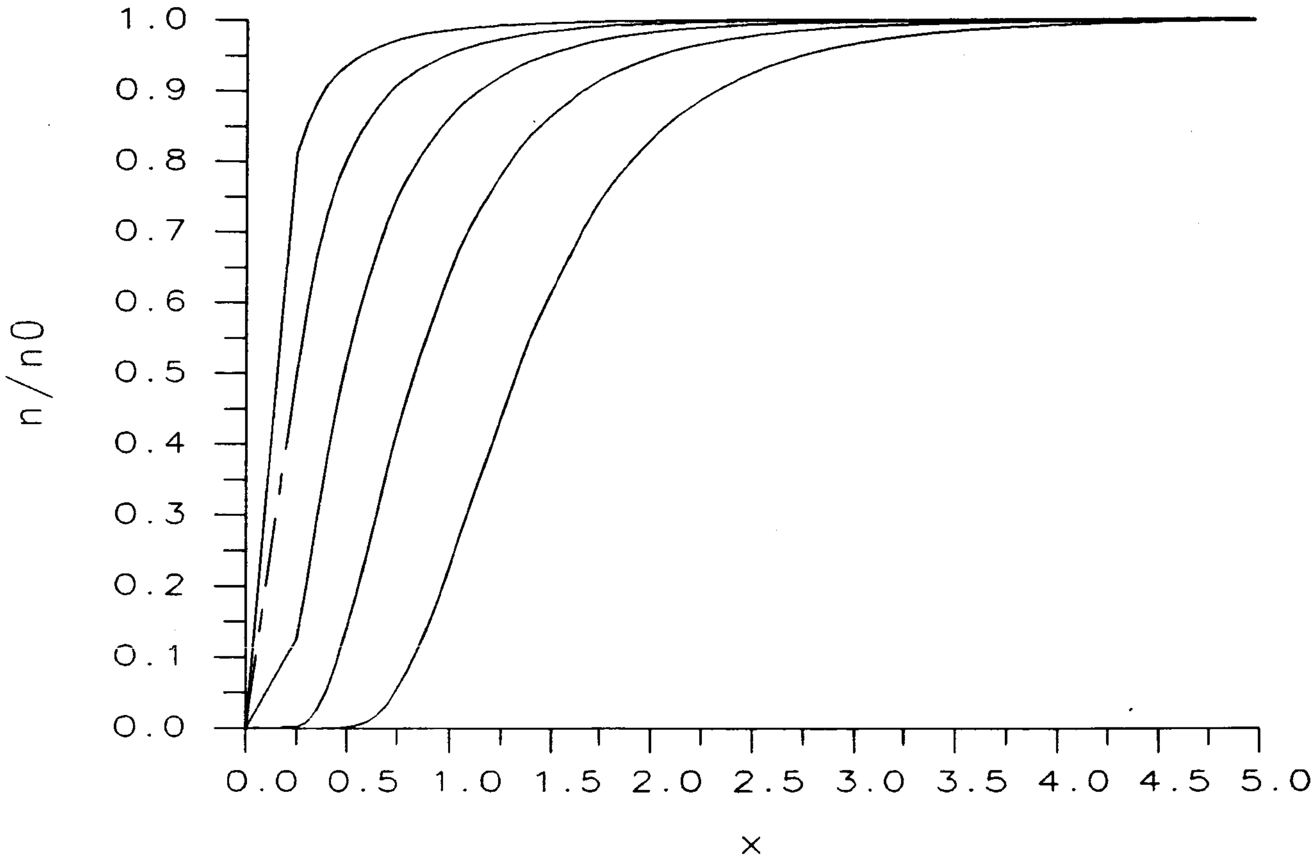


Figure 1. Ionospheric Particle Density vs. Upstream Distance

4.0 REFERENCES

1. Barnett, A. and S. Olbert, 1986. "Radiation of Plasma Waves by a Conducting Body Moving Through a Magnetized Plasma." Journal Geophys. Research <u>91</u>, 10117.

2. Stenzel, R.L. and J.M. Urrutia, 1986(a). "Laboratory Model of a Tethered Balloon — Electron Beam Current System," Geophysical Research Letters, <u>13</u>, 797-800.

3. Urrutia, J.M. and R.L. Stenzel, 1986(b). "Anomalous Currents to an Electrode in a Magnetoplasma," Physical Review Letters, <u>57</u>, 715-718.